

## TECHNICAL NOTE

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# GENERAL PROCEDURE FOR CLOTHING EVALUATIONS RELATIVE TO HEAT STRESS

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May 1995

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This technical note (TN) describes the recommended biophysical and physiological test procedures for heat stress evaluations of textiles and clothing. The emphasis in this TN is on the human physiological testing, which is required as part of the development and acquisition process for Army materiel, in support of the Health Hazard Assessment (HHA) which is conducted by the U.S. Army Center for Health Promotion and Preventive Medicine, provisional. Biophysical evaluations for clothing include determination of the thermal characteristics for textiles via guarded hot plate tests, and for clothing systems via thermal manikin tests. Mathematical models are used to predict performance for evaluation conditions and/or field use. Human physiological testing for clothing is best done in a controlled laboratory environment, although field trials may also be conducted. Tests must control for confounding variables, and proven test and measurement methods must be employed.

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## FOREWORD

The scientists at the U.S. Army Research Institute of Environmental Medicine (USARIEM) have been conducting clothing evaluations for more than 30 years. For the past ~8 years we have worked directly with the former U.S. Army Environmental Hygiene Agency, now (as of Sept 1994) the U.S. Army Center for Health Promotion and Preventive Medicine, provisional (CHPPM[P]), on clothing evaluations in support of Army materiel development and acquisition. While we have developed in-house procedures for our clothing evaluations, we have not officially documented nor published our standard operating procedure (SOP). Since May 1992, a draft SOP for clothing evaluations has been used at USARIEM and distributed to CHPPM(P) and to other DoD laboratories where clothing is evaluated. (Sawka and Gonzalez, (Draft) 14 May 1992.) It is our intention that this technical note provide information and guidance, and serve as the SOP pertaining to the evaluation of clothing relative to heat stress.

A memorandum from The Army Environmental Hygiene Agency (from HSHB-MO-A, MAJ David J. Tompkins, April 23, 1992), for the Commander at the U.S. Army Research Institute of Environmental Medicine, ATTN: SGRD-UE-ZB (LTC Glenn), Natick, MA 01760-5007; Subject: AMEDD Heat Stress Strategy, requested an SOP and led Drs. Sawka and Gonzalez to write their 14 May 94 SOP for Heat Stress Testing. This technical note is based on their SOP.

## **ACKNOWLEDGEMENTS**

The authors acknowledge the ongoing dialogue with the U.S. Army Center for Health Promotion and Preventive Medicine, (provisional; until recently, known as the U.S. Army Environmental Hygiene Agency). We would like especially to thank LTC George Murnyak and LTC David Mukai for their help over the past few years. Our understanding of their needs contributes to a more relevant clothing evaluation and to a more meaningful Health Hazard Assessment. In addition, we acknowledge (at USARIEM) MAJ Sven Ljammo and (formerly at USARIEM) COL John Glenn for their insights, which have also enhanced our understanding of the Health Hazard Assessment process.

## EXECUTIVE SUMMARY

This technical note (TN) describes the basic test procedures employed to evaluate clothing relative to heat stress. Included are the recommended biophysical and physiological tests for fabric and clothing. The emphasis in this TN is on the human physiological testing. As part of the development and acquisition process, Army materiel must undergo a Health Hazard Assessment (HHA) which is conducted, and a report is written, by the U.S. Army Center for Health Promotion and Preventive Medicine, provisional (CHPPM[P]). One of the most serious health hazards related to clothing systems, especially impermeable chemical protective clothing, is heat strain. With respect to the thermal characteristics of clothing and heat strain, USARIEM has been a key clothing evaluator for the Army for more than 30 years. Since the mid-1980s, USARIEM has worked in close concert with CHPPM(P) in evaluating the heat stress effects of clothing systems, and in developing optimal evaluation procedures.

Biophysical evaluations for clothing include determination of the thermal characteristics (vapor permeability and insulation) for fabrics, via guarded hot plate tests, and for clothing systems, via thermal manikin tests. The results of the biophysical tests can be used to select the fabric or clothing with the best thermal characteristics. The data from manikin evaluations can be used in the USARIEM Heat Strain Model. The model can be used to predict performance for conditions that are too risky, too numerous, or too costly to evaluate using volunteers. If results of manikin tests and modeling indicate clothing differences that may be discernible in human trials, the garment system may proceed to human laboratory and possibly field evaluations.

Human physiological testing for clothing is best done in a controlled laboratory environment, although for realism and user acceptability, field trials may also be conducted. Tests must control for confounding variables. (Subjects serve as their own controls, and test environment and procedures are consistent between trials.) Proven test and measurement methods must be employed. Currently these include measurement of core body temperature either via esophageal or rectal temperature probe, measurement of skin temperatures, heart rate, and sweating rate.

## INTRODUCTION/BACKGROUND

The purpose of this technical note is to serve as a guide for the evaluation of clothing systems relative to the heat stress they may add to, and the heat strain they may cause in the wearer. The clothing evaluations described are generally conducted to compare a prototype to the standard and to select a garment from among several candidates. An evaluation is required when the existence of the health hazard, heat stress, has been suspected or identified in a newly developed or fielded item. The biophysical and human physiological evaluation procedures described (briefly and in detail, respectively) are consistent with test methodologies that can be used to provide data and information to the U.S. Army Center for Health Promotion and Preventive Medicine, provisional (CHPPM[P]), for the Health Hazard Assessment (HHA). As part of the development process, Army materiel must undergo a HHA. The HHA report (IAW AR 40-10) is written by CHPPM(P).

One of the most serious health hazards related to clothing systems, especially impermeable chemical protective (CP) clothing, is heat strain. With respect to the thermal characteristics and heat (and cold) strain, USARIEM has been a key clothing evaluator for the Army for more than 30 years. Within the last 8 years the biophysicists and physiologists at USARIEM have worked in concert with CHPPM(P) in evaluating clothing systems and in developing optimal evaluation procedures. Typically, garments tested for the HHA include developmental, new and/or improved duty uniforms and CP clothing used by military or civilian DoD personnel.

Throughout this paper, the term "heat stress" (HS) will refer to the environmental drivers or parameters related to the mission that may cause the stressed individual to store heat; while "heat strain" will refer to the physiological responses in the individual. Heat stress is the product of an interaction of mission (uniform worn, load carried, terrain, work rate) and environment (temperature, humidity, solar radiation, wind speed), with physiological factors (fitness, hydration, acclimatization, rest, nutrition, medication, health) (Sawka and Wenger, 1988).

A clothing system's contribution to heat stress may cause or exacerbate heat strain. In vehicles and shelters, when temperature and humidity reach intolerable levels, even air conditioning the enclosed space might be inadequate if persons working in that space must wear CP garments. In these cases the CP garment systems should include microclimate cooling. Clothing systems, especially CP garments, can interfere with thermoregulation by impeding evaporation of sweat and dry heat dissipation. If physical work load is expected of persons wearing CP garments, heat strain will be exacerbated, performance will be limited (Montain et al., 1994), and the potential for heat injury will be increased. (The reader is referred to DoD MIL-STD-1472D for temperature requirements and other information regarding vehicles and shelters. MIL-STD-210C, MIL-STD-882C, MIL-HDBK-759A, and DoA AR 70-38 will provide the reader more information regarding HHA relative to design/engineering and evaluation of military materiel.)

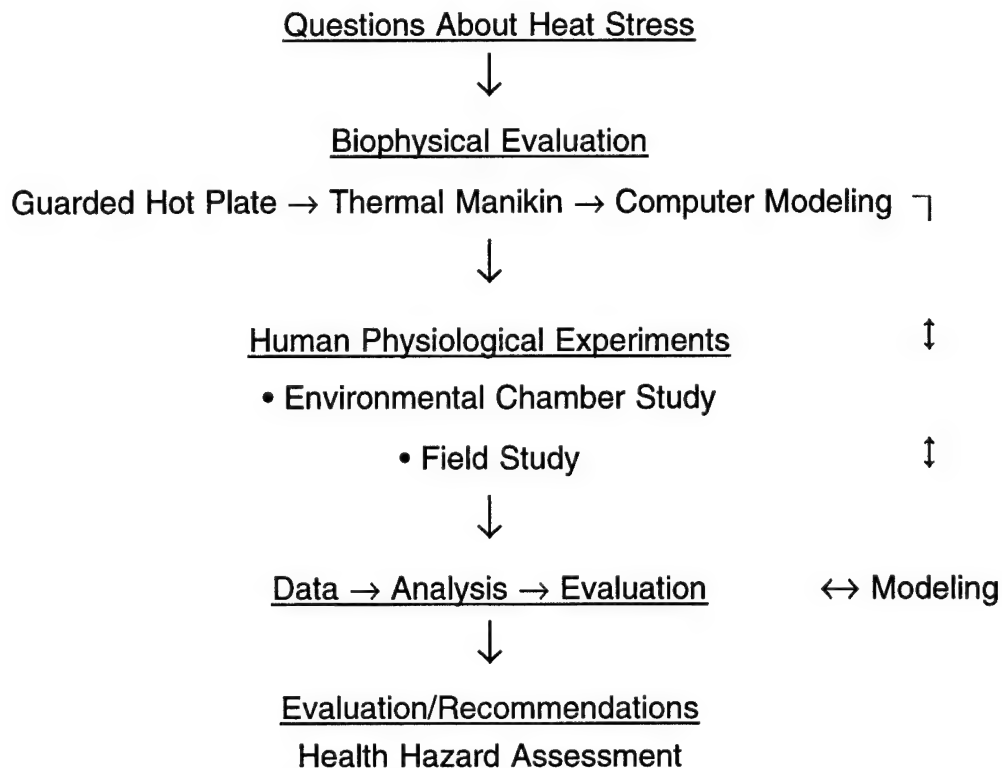
Humans can maintain normal body temperature within a wide range of heat stress (Sawka and Wenger, 1988). The normal mechanisms for heat dissipation are via dry (radiation and convection) and evaporative heat loss. These mechanisms are affected by peripheral vasodilation, which augments heat transfer from core to skin via increased blood flow and via evaporative heat transfer by activation of sweating. The cardiovascular response to HS includes increased heart rate and decreased blood flow to the gastrointestinal tract and other inactive tissue to maintain blood flow during peripheral vasodilation. Physiological symptoms of heat strain include elevated sweating rate, heart rate, and body temperature. When the heat load exceeds the body's ability to dissipate heat, and heat strain is allowed to progress, heat illness/injury can occur. Pathological states of heat strain include heat cramps, heat exhaustion, heat stroke, and the potential for reversible or irreversible (especially neurological) tissue damage. (See DoD TB MED 507, 1980 and Burr, 1991 for a description of these heat illnesses.) Performance decrements (physical and mental) can occur at hyperthermic and/or dehydration levels lower than those causing heat injury (Sawka and Pandolf, 1990).

The following sections describe the recommended test process and methodology for conducting clothing evaluations (relative to heat stress) in support of the HHA. Biophysical testing includes a logical sequence of tests from guarded hot plate to

thermal manikin to prediction modeling. Physiological testing includes human laboratory (environmental chamber) and field studies. Figure 1 illustrates the conceptual framework for heat stress evaluations in support of the HHA process.

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HEAT STRESS AND CLOTHING SYSTEMS  
APPROACH TO EVALUATIONS FOR  
HEALTH HAZARD ASSESSMENT



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Figure 1. Flowchart representing the relationship among the tests used to evaluate clothing systems relative to heat stress.

## BIOPHYSICAL EVALUATION

The initial testing of clothing systems should begin with a biophysical evaluation of the textile material, followed by an evaluation of the actual garment ensemble. This paper will outline the recommended tests to be included in a biophysical evaluation. (For more detailed information on biophysical textile and clothing tests, see Gonzalez, 1988; Gonzalez et al., 1993 and Gibson et al., 1994)

Samples of the material(s) employed in the proposed clothing system are tested for both thermal and water vapor resistance on a guarded hot plate apparatus, which is operated in accordance with International Organization for Standardization (ISO, 1993). Following material tests, a Copper Manikin evaluation is necessary for each new clothing system proposed. This allows determination of the thermal insulation (clo) and the vapor permeability ( $i_m$ ) of the specific clothing system to be considered in the HHA. These data are used to develop heat exchange coefficients ( $i_m/\text{clo} =$  evaporative resistance). Clothing coefficients derived from experiments at various ambient air velocities are used as input for human heat strain modeling. The currently used (standard) material and clothing system should be used as the control.

Heat Transfer Terms used in the biophysical evaluation of the thermal characteristics of fabrics and clothing:

Clo	Unit of resistance to heat flow through fabric or clothing (INSULATION) 1 Clo = 6.46 W/m <sup>2</sup> of surface area per degree Celsius difference between $T_{\text{skin}}$ and $T_{\text{ambient}}$
$i_m$	Permeability Index for evaporative heat loss (PERMEABILITY) A dimensionless number from 0 to 1, zero being impermeable
$i_m/\text{Clo}$	Ratio of permeability to insulation (EVAPORATIVE RESISTANCE) The higher the $i_m/\text{Clo}$ , the more potential for evaporation and, therefore, heat loss.

**Guarded Hot Plate** (thermoregulatory model of human skin): Guarded Hot Plate (GHP) testing measures the dry and wet (evaporative) heat transfer of single or multiple layered textile materials. Materials are placed on a temperature-controlled hot plate in a controlled environmental chamber. This procedure is designed to simulate the transfer phenomena that occur in the microclimate created between the skin surface, the various resistive textile layers, and the surrounding ambient atmosphere. An advantage of GHP testing is that it can be used to screen and rank a large number of materials. (For a detailed description, the reader is referred to ISO, 1993; Endrusick, 1993). A limitation of GHP testing is that the thermal resistance and vapor permeability measured for flat material samples are not necessarily the same as when the material is worn in an ensemble. Although ranking probably will not change, differences measured on the GHP may be larger than those measured on a manikin. If GHP tests show that a material is significantly better than the standard or control ( $>0.1$  Clo or  $>0.03$   $i_m$ /Clo difference), and/or if the material passes a cut based on ranking, that material proceeds (in the clothing ensemble) to Thermal Manikin (TM) Testing.

**Manikin**: Thermal manikin testing measures dry and wet heat transfer of garment ensembles worn by a heated copper manikin in a controlled environmental chamber. Thermal insulation ( $I_T$ ) and evaporative potential (Woodcock vapor permeability index ( $i_m$ )) of clothing ensembles shall be evaluated using standard operating procedures (SOP) on a life-size copper manikin (Gonzalez et al., 1993; Breckenridge, 1977; Woodcock, 1961; Woodcock, 1962; Woodcock and Breckenridge, 1965). The copper manikin, equipped with computer-controlled capabilities, must be encapsulated by a form-fitting cotton "skin" that can be used to represent a nonsweating condition, or to simulate a sweating human with a 100% wetted surface area by completely saturating the skin with distilled water. A standard reference garment (i.e., BDO or other U.S. Army standard issue item) should be used as a reference control to compare the thermal properties of each prototype ensemble being evaluated (Breckenridge, 1977).

Standard procedures should be used in operating the manikin. These procedures include the regulation of manikin surface at a constant 33°C temperature. Control of the air temperature, relative humidity and air velocity in the climatic chamber is also essential to assure good data collection. The conditions in the climatic chamber shall

be maintained as close as possible to 27 °C, 50 %RH: the classic definition of thermal neutral conditions (ASHRAE, 1993; Gagge, Stolwijk, and Hardy, 1967). The air velocities in each of the chambers shall be varied from "still air,"  $\sim 0.4 \text{ m}\cdot\text{s}^{-1}$  ( $\sim 0.9$  mph), to  $3 \text{ m}\cdot\text{s}^{-1}$  (6.7 mph), which is the upper limit of the environmental chamber. It is necessary that testing be done in at least three different wind speeds to allow accurate determination (and prediction) of the effect of air movement on the thermal properties of the clothing (Gonzalez et al., 1989).

This testing accounts for heat transfer effects of the material, and for garment design and fit as well. The advantages of TM testing (using simulation of heated and sweating skin) are that use of a heated, "sweating," computerized manikin allows thermal resistance and vapor permeability to be evaluated on the complete clothing ensemble. Articulated manikins also allow for measurement of air movement and "pumping" action of air within the clothing. The limitations of TM testing are that the static manikin does not allow measurement of movement and pumping effects on thermal resistance and vapor permeability. Thermal manikin testing must be done at three or more different wind speeds if a range of conditions will be modeled. The results of TM testing can be entered into mathematical computer programs that predict human responses under a variety of environmental and work intensity conditions. If TM tests indicate there is enough difference ( $\geq 0.1 i_{m}/clo$ ) between ensembles to be within the resolution of human testing, it is usually recommended that the ensemble go on to human testing. In any case, the TM results can be used in a prediction model as outlined below. If the TM differences are so small ( $< 0.1 i_{m}/clo$ ) as to most likely be indiscernible by human testing, modeling alone may be used. Cases are discussed, and decisions regarding testing are made in concert with CHPPM(P). (Sometimes human testing is requested for documenting human responses, even when clothing comparisons are not made or are not likely to reveal significant differences.)

**Modeling:** The results of TM testing can be entered into mathematical computer models (Gonzalez and Stroschein, 1991; Gonzalez et al., 1993; Pandolf et al., 1986) that predict human responses under a variety of environmental and work intensity conditions. Thermal properties (as determined on the manikin) for a particular clothing system are introduced as input to the current USARIEM Heat Strain Model (and can also be used in future prediction models). The USARIEM Heat Strain Model uses the

thermal coefficients from the given prototype clothing evaluation to arrive at predicted core temperature, maximum endurance times, optimal work/rest cycles, and water requirements for soldiers performing typical military tasks. In general, light (172 to 325 watts), moderate (325 to 500 watts), and heavy (greater than 500 watts) work rates signify appropriate metabolic output for soldiers exposed to the climatic conditions being investigated (Pandolf et al., 1986). The advantages of modeling are that predictions can be made for a wide variety and combination of input variables (wide range of environment; light, moderate, heavy for work loads and casualty rates; MOPP levels [FM 3-4]; condition of the troops, etc.) The limitations are that not all conditions can be modeled, or are done so with qualification, because the existing data bank is incomplete in some areas.

From these data it is possible to predict the individual's tolerance time in the various temperature/humidity scenarios encountered during field operations. The basis for establishing probability of heat casualty derives from prediction of equilibrium core temperature for an individual during work and recovery for the various inputs specified with each clothing system (see spreadsheet table examples in the various USARIEM pocket guides, Technical Notes: 93-1 Somalia, 93-6 Yugoslavia, 94-3 Rwanda, 94-4 Haiti, 95-1 S-W Asia). Specific manikin and heat strain prediction modeling allow comparisons to be made between the standard and the test garments. Predicted values may be used in determining if subsequent physiological chamber evaluations are necessary.

**Spreadsheet of Biophysical Modeling Results:** Predictive modeling for the HHA, using the thermal characteristics of the clothing determined from the copper manikin evaluation, are accomplished using the USARIEM heat strain model. The model input parameters, in addition to measured clothing values, are listed below (see Table 1).

Table 1. USARIEM Heat Strain Model; Typical Input and Output Parameters

Typical Input Parameters

Soldier, work, clothing:

1. 18 to 22 year old Soldiers
2. Physically fit males
3. Fully heat acclimated
4. Light work rate (range of 172-325 watts)
5. Moderate work rate (range of 325 to 500 watts)
6. Heavy work rate (500 to 600 watts)
7. MOPP level, Clothing system open/closed

Environment:

8. No Solar Load (Indoor mode set match human chamber tests. If field-relevant predictions are desired, solar load [clear sky, cloudy, or partly cloudy] can be added as an input parameter.)
9. Wind Speed 2.24 m/s (5.0 mph) and 4.4 m/s (10 mph)
10. Jungle:  $\bar{T}_a = 35\text{ }^{\circ}\text{C}$  (95  $^{\circ}\text{F}$ ); 75 %RH. <sup>1</sup>
11. European:  $\bar{T}_a = 20\text{ }^{\circ}\text{C}$  (68  $^{\circ}\text{F}$ ); 40 %RH.
12. Desert #1:  $\bar{T}_a = 49\text{ }^{\circ}\text{C}$  (120.2  $^{\circ}\text{F}$ ); 20 %RH.
13. Desert #2:  $T_a = 40\text{ }^{\circ}\text{C}$  (104  $^{\circ}\text{F}$ ); 30 %RH

Casualties:

14. Light casualties: <5% of troops reaching a core temperature of 39.0  $^{\circ}\text{C}$  (102.2  $^{\circ}\text{F}$ ) during a maximum work effort
15. Moderate casualties: 20% of troops reaching a core temperature of 39.5  $^{\circ}\text{C}$  (103.1  $^{\circ}\text{F}$ ) during a maximum work effort
16. Heavy casualties: 50% of troops reaching a core temperature of 40.0  $^{\circ}\text{C}$  (104  $^{\circ}\text{F}$ ) during a maximum work effort

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<sup>1</sup>While 75% RH is the standard "jungle" environment for biophysical testing and modeling, 50% RH is recommended for human testing.

The modeling outputs include the following:

1. Work/Rest cycles on an hourly basis (minutes per hour).
2. Maximum continuous one-time work effort (in minutes) to reach 39 °C, 39.5 °C and 40 °C with no rest cycles.
3. Water requirements in canteens/hour for both the work/rest and the one-time work efforts.

The modeling results for specific candidate systems and standard issue counterparts should be presented in tabular format and graphical format (with core temperature on the y-axis and time in minutes on the x-axis). For more information about the model, see Pandolf et al., 1986; Pandolf et al., 1993; Pandolf et al., 1995; and Gonzalez and Stroschein, 1991. For an example of how modeling predicts actual performance, see Pandolf et al., 1995. For examples of the output parameters, and for recommendations based on the predictions, see DoA FM 3-4 or any of the USARIEM pocket guides listed in the reference section (USARIEM Technical Notes: 93-1, 93-6, 94-3, 94-4, 95-1).

## PHYSIOLOGICAL EVALUATION

Careful consideration should be given to the limitations and costs of human physiological testing before proceeding. Medical, cost and time considerations, as well as biological variability, impose more limitations on human testing compared to hot plate or manikin testing. Advantages of human laboratory testing are that data collected from real people (vs. manikin) are perceived to be, and can be, reliable and valid. Human physiological testing should be included in the clothing evaluation if biophysical analyses and/or prediction modeling indicate that (thermal) differences between clothing systems are sufficient to be within the resolution of physiological measurements. Field studies are often included to provide the user community with information from a more realistic setting. Also, CHPPM(P) may determine that such data are required, after giving consideration to the intended use for, and stated requirements of, the clothing system(s). Once the decision to proceed has been made, careful consideration should also be given regarding appropriate test methodology.

### Test Planning Considerations

Since even a homogeneous group of human test subjects display considerable interindividual thermoregulatory variability, every effort must be made to account for variables within the investigator's control if meaningful data are to be collected. Because of this variability, and since relatively few subjects can be tested (usually 8-15), the following should be considered when planning garment comparison tests.

1. Each subject must serve as his or her own control in a repeated measures test design. That is, each test subject must participate in each trial to be used in the comparison. A test design that is not appropriate is one in which a group of subjects wearing one type of garment is compared to a another group wearing a different type of garment.

2. Any prototype or newly improved garment to be tested must be compared to the standard as the control garment. The control garment must be tested in the same

tests, with the same subjects, as the prototype garments. Previous test data, collected on a different group of subjects under the same or different conditions, cannot be directly compared to newly collected data.

3. Counterbalanced (not randomized) trials ensure that each garment is equally represented in the first, middle and last days of testing for each subject. This means that each test garment will be worn on a different test day for each test subject to eliminate any learning curve or other affect of test order.

4. Subjects should be well rested, and all comparable trials should be conducted at approximately the same time of day to control for circadian periodicity effects on thermoregulation, as baseline core temperature varies  $\sim 0.6^{\circ}\text{C}$  in the course of a day and/or with sleep deprivation (Stephenson et al., 1984; Stephenson and Kolka, 1988).

5. Subjects should be exercise-heat acclimated if two or more comparative trials are to be conducted within  $\sim 3$  days of one another. Also, acclimated, fit subjects are better able to exercise in the heat, and are able to remain in the heat longer, recover faster, and provide more usable data from their tests (Wenger, 1988). Acclimation procedures are discussed later.

6. Subjects should be well nourished and well hydrated for at least 24 hours prior to and throughout the heat stress testing. Baseline body weights taken during the acclimation process and throughout testing serve to alert test subjects, technicians, and investigators of progressive dehydration (which is common unless specific attention is paid to maintaining hydration status). As little as 1% dehydration (measured as a decrease of 1% of body [water] weight) can adversely affect performance (Sawka and Pandolf, 1990).

7. Subjects should also be healthy (see later section on Test Subject medical clearance), as thermoregulation (besides subject well-being) is affected by fever, skin disorders, and some medications.

8. Regarding the use of female test subjects, if there are stringent time or resource constraints (this reason is not acceptable to the USARIEM Scientific Review

Committee), consider testing only male subjects. The use of female subjects would require a much larger sample size (3-4 times larger) and/or a longer time commitment to control tests for the effects of menstrual cycle phase on thermoregulation. If possible, clothing tests for female volunteers should be scheduled on days 2-8 of their menstrual cycle. Since women tested during the early follicular phase of the menstrual cycle (days ~1-10) have been shown to have similar thermoregulatory responses compared to men (Kolka, communication as part of The Presidential Commission on the Assignment of Women in the Armed Forces, in press; Kolka, Stephenson, and Gonzalez, 1994; Kolka et al., 1987; Stephenson and Kolka, 1993), all the subjects' data (male and female) can be analyzed together. If women are tested during the late follicular or luteal phases of their cycles, all of their tests should be controlled for cycle phase. That is, each of their tests must be conducted during the same time of their menstrual cycle, to avoid the confounding variable of changing baseline core temperature. In this case, data should be analyzed separately to minimize interindividual variability. Women's baseline temperatures increase ~0.4 °C from the follicular to the luteal phase (Stephenson and Kolka, 1993; Stephenson and Kolka, 1988; Kolka (as above), 1994-5; Kolka et al., 1994; Kolka et al., 1987), while the test procedures allow measurement of differences in core temperature ranging from 0.2-0.5 °C (Quigley et al., 1992).

9. Concerning the use of "mission-relevant" equipment, accessories or activities during garment heat strain evaluations, attempts to make the standard thermoregulatory evaluations more mission-relevant should be avoided, as the addition of nongarment variables confounds assessment of thermal strain. The use of nonsteady-state exercise should be avoided because rapid fluctuations in metabolic heat production (and core body temperature) obscure garment comparisons. For field studies, realistic (user-acceptable) exercise activities may be used if they meet the test criteria for moderate, steady-state exercise that is repeatable. Use of military equipment such as backpacks and body armor interfere with heat exchange and should not be used unless they specifically are being tested, or are required to be included by the HHA. Likewise, protective masks increase resistance to breathing and can adversely influence exercise performance (Muza, 1986). To avoid this influence, the mask's filters may be removed when possible so that they do not confound the thermal evaluation. The most pervasive effect of these nongarment items is to

decrease the time a subject can test. If subtle differences between garments may not emerge until well into the test time, early removal from tests serves to obscure differences that may exist. It is important to keep in mind the question(s) that the study is designed to address.

Close monitoring of the environmental conditions is essential, as even in relatively consistent environments, day-to-day fluctuations can jeopardize data. If possible, postpone testing until the correct test conditions return. If testing must proceed, consider using an analysis of covariance in the statistical analysis. (see Figure 3 and discussion p. 26).

In addition, prior to the evaluation of heat strain, volunteers should be familiar with wearing the garment ensembles to be tested. Part of the familiarization should include the work/exercise they will be performing and the instrumentation to be used during testing.

### **Test Subjects**

For any clothing evaluations including human test subjects, the following information is applicable. Investigators must adhere to guidelines established for research on humans. At USARIEM these are AR 70-25, USAMRMC 70-25, and USARIEM 70-25 on the Use of Volunteers in Research, and USARIEM M 70-68 on Quality Assurance for Research at USARIEM. Most research related to garment systems or other materiel is within the framework, restrictions, and safety limitations of the USARIEM Type Protocol.<sup>1</sup>

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<sup>1</sup> Most recent update approved 7 December 1994. The USARIEM Type Protocol (Human research studies in the areas of thermal, hypoxic and operational stress, exercise, nutrition and military performance) provides information and explanations about conditions, standards and safeguards, in order to serve as an encompassing framework for specific in-house studies in its general subject area. It is used as a reference to facilitate the understanding and review of specific study protocols which conform to its provisions, and thus do not exceed the degree of risk, and safety limits therein stipulated (reference paragraph 18, USAMRDC Reg 70-25, 3 May 1989).

All volunteers selected to be test subjects should be healthy, relatively fit (Armstrong and Pandolf, 1988), 18-35 years old, and must be medically cleared to participate in the study. Age exceptions can be made for studies of garments to be used for older individuals, but more extensive medical clearance is required.<sup>2</sup> Volunteers with a history of heat injury or chronic respiratory illness, or orthopedic problems that might be exacerbated by treadmill exercise in the heat, should not be selected. Thermoregulation is also affected by fever, some medications (especially anti-inflammatory and antihistamines), skin disorders and sleep deprivation (Stephenson and Kolka, 1988; Sawka et al., 1993). Male volunteers who meet medical clearance and any test-specific criteria may be selected as test subjects. Female volunteers who are not pregnant and who meet medical clearance and any test-specific criteria may also be selected as test subjects.

Test subjects should not be sleep deprived and should be asked to get ~8 h of sleep each night (Stephenson and Kolka, 1988), and to refrain from: drinking alcohol (Freund et al., 1994), taking over-the-counter medications (antihistamine, anti-inflammatory), and participating in heavy/vigorous exercise, for at least 12 hours before acclimation and 24 hours before tests. If a subject regularly exercises, a normal routine may be maintained but as stated above, heavy exercise should be avoided prior to testing. Smokers should be asked to refrain from smoking for at least 2 hours prior to a test, until testing is completed for that day. Any of these precautions listed can effect thermoregulation.

### **Exercise-Heat Acclimation**

Prior to any garment tests, subjects should participate in a 5-10 day exercise-heat acclimation process (Wenger, 1988). Additional acclimation is not necessary for field studies using volunteers who have been living and working (for at least one week) in a hot climate, the same or similar to the test site. Acclimation prior to testing will ensure that thermoregulatory status will not change during testing. In addition, heat

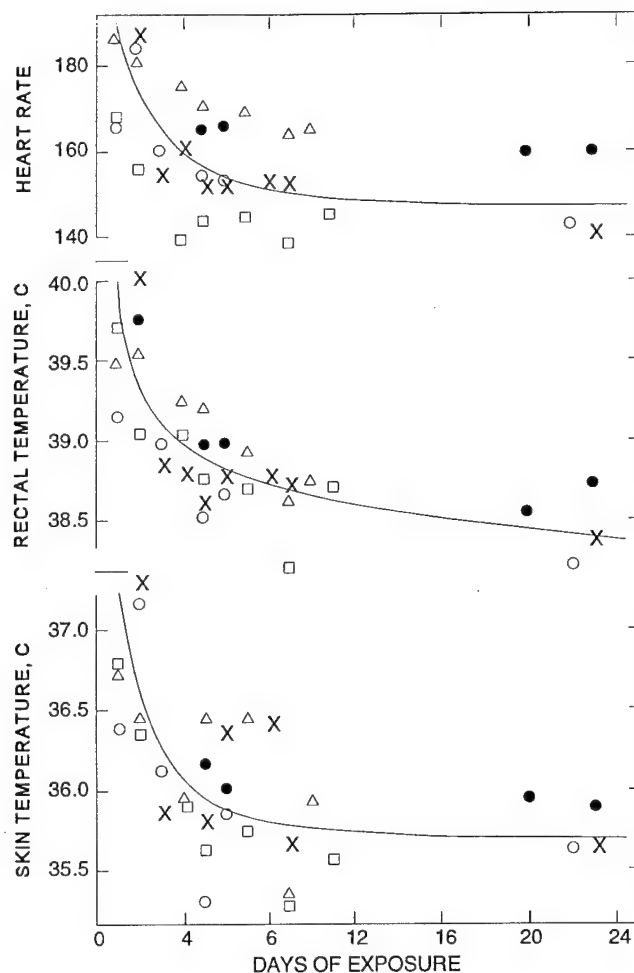
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<sup>2</sup> Medical clearance criteria include medical history and exam as per USARIEM Type Protocol and USARIEM-M 70-25

acclimation will provide an advantage to subjects so that they will have a better chance of completing the tests (Wenger, 1988). Each day of heat acclimation should consist of ~120 min in the heated chamber, ~100 min of which is spent exercising. During the acclimation sessions, subjects should be monitored for core body temperature (rectal temperature) and heart rate. Acclimation may include work/rest cycles or continuous work. The exercise segments should be of moderate intensity (~350-450 W or ~30-50%  $\dot{V}O_{2\max}$ ) at least 50 min long. While treadmill walking is recommended (most easily quantifiable/repeatable exercise, most often used during the garment tests), exercise may include cycle ergometry or a combination of the two. (Other aerobic exercise at similar intensity, such as on a rowing ergometer or stair stepping ergometer, may also be used). For some subjects treadmill exercise for several days in a row causes foot blisters and/or foot, knee, or leg problems. In this case an alternative such as cycle exercise is especially helpful.

Figure 2. These graphs illustrate a 24-day plateau effect on heart rate (beats per min), rectal and skin temperatures ( $^{\circ}\text{C}$ ), during exercise-heat acclimation in 5 men.

(Redrawn [with permission] from Robinson et al., 1943, p 168)



The environmental conditions should be between  $\sim 35\text{-}40\text{ }^{\circ}\text{C}$  ( $\sim 95\text{-}104\text{ }^{\circ}\text{F}$ ) and relative humidity  $\sim 20\text{-}60\%$ . An ideal acclimation environment for clothing tests is  $T_{db}$   $40\text{ }^{\circ}\text{C}$  ( $\pm 1\text{ }^{\circ}\text{C}$ ),  $T_{dp}$   $19.2\text{ }^{\circ}\text{C}$  ( $\pm 1\text{ }^{\circ}\text{C}$ ),  $\sim 30\text{ \%RH}$  ( $\pm 2\%$ ), with wind speed from  $\sim 1\text{-}3\text{ m}\cdot\text{sec}^{-1}$  ( $\sim 2.2\text{-}6.7\text{ mph}$ ). These conditions, usually more severe than the test environment, better prepare subjects for tests in encapsulating clothing.

During acclimation, subjects should dress in shorts, T-shirt, socks and comfortable athletic shoes. Treadmill speed (or cycle resistance) should be set so as to elicit  $\sim 30\text{-}50\%$  of maximal aerobic power. (Our tests are usually  $\sim 1.34\text{-}1.56\text{ m}\cdot\text{sec}^{-1}$  ( $3\text{-}3.5\text{ mph}$ ),  $0\text{-}4\%$  grade.) Final values for  $T_{re}$  and HR should be used to determine acclimation status. The same time point (e.g., all values at 100 min or 120 min) must be used for day-to-day comparisons. Acclimation is complete when day-to-day changes (decreases in core temperature and heart rate) plateau; when there are no significant differences for three successive days (see Figure 2).

## **Hydration**

Subjects should be well hydrated throughout acclimation and for at least 2 days prior to and including test days (Sawka and Pandolf, 1990). Tests that restrict fluid intake should be avoided unless hydration status is a specific focus of the test. Hydration should be assessed by daily baseline weights taken each morning during acclimation and testing, and by subjects paying attention to the color of their urine. To maintain hydration, subjects should eat regular meals and drink plenty of nonalcoholic, noncaffeinated beverages between sessions in the heat. They should be briefed on the importance of this in the consent form, and reminded of it throughout the study. In order to prevent dehydration, subjects should drink at least 200 ml water or commercial glucose-electrolyte beverage (sport drink) while dressing and being instrumented, and then drink water *ad libitum* throughout the remainder of each acclimation session. Within 120 min of the start of each garment test, subjects should consume 200-500 ml water or sport drink. The solutes contained within the sport drink (most commercial drinks have similar compositions) will enable a reduced urine output and therefore enable more fluid to be retained, compared to drinking only water (Committee on Military Nutrition Research, 1993 and 1994; Nadel et al., 1990).

During the heat stress experiments, rehydration should be with water (at a volume equal to the sweating rate, when possible) in a programmed manner, by using either the Fist-Flex system or by passing flexible tubing (used as a drinking straw) under the mask if subjects are in MOPP 4. To ensure euhydration during acclimation, subjects can be weighed during a rest break and given water (or sport drink) to replace fluids lost during exercise.

Subjects should be encouraged to drink during and between all sessions in the heat. Subjects may be allowed to drink *ad libitum* during testing unless they are not trained and experienced in working in the heat. Fluids should be provided whenever the subjects are at the test site. Dressed weights should be measured at least once per hour. After the first hour assume garments contain a steady-state volume of unevaporated sweat (~1 liter for the BDO with no duty uniform in moderately hot desert environment -- use laboratory experience if available), and administer fluid replacement to correct body weight by the appropriate amount. Pre- and post-session nude (or minimally clothed) weights should be measured, and any fluid losses (measured as decreases in body weight) should be replaced either while the subjects are still at the test site, or within the next few hours. Pre-exercise weights will serve as baseline measurements to observe possible day-to-day dehydration. Based on our experience with previous garment tests and calculations from the USARIEM Heat Strain Model (Pandolf et al., 1986), we expect ~2 L loss, of which subjects typically replace ~1 L during a 2-hour session. Since it is often uncomfortable to drink more than 400-500 ml during the first 30-60 min after exercise, any amounts greater than this which a subject has not replaced by the time he or she is ready to leave the test site may be provided as a take-home sport drink or fruit juice.

## **Experimental Procedures**

**Familiarization:** Prior to experimental trials, each subject should be familiarized with wearing the entire garment ensemble to be tested, and with the exercise to be employed in the test. Familiarization with the garments or activities may not be necessary for volunteers who have been training and/or working in the test garments. These familiarization sessions can also serve as determinants for the exercise

intensity to be used during testing. Metabolic rate, determined during several 15-20 min walks on the treadmill at various speed/grade combinations, can serve to select the desired intensity and, at the same time, to familiarize the subjects with the test garments and exercise. In addition to these sessions, if the clothing ensemble includes a CP mask, familiarization with the mask can be included in the acclimation sessions. Wearing the mask for increasing periods of time during acclimation (e.g., for ~10-15 min first or second day, next day ~20-30 min, etc., until mask can be tolerated for 60 min or more) decreases the likelihood that subjects will terminate testing because of discomfort due to the mask.

Physiological testing required for the HHA should be conducted in a carefully controlled environmental chamber, as the daily variations in environmental conditions and work load in field studies (even under the best possible conditions) will often negate the differences between clothing systems. The environmental/work load conditions should follow the guidelines used for modeling, when possible; however, unique statement-of-need and/or user requirements may require deviation from these guidelines.

**Environmental Conditions:** Measurement of ambient conditions should include dry bulb, dew point or wet bulb, and black globe temperatures, as well as wind speed. Environmental conditions should be controlled within  $\pm 0.5$  °C so that discrimination among experimental conditions is possible. The test environment chosen (relative to clothing and exercise intensity used) should enable steady-state measurements for at least 60 min. Extreme temperatures/humidity should be avoided as they limit the time in which data can be collected, and thus limit possibilities for statistical comparison. For human testing, the suggested conditions are Temperate 20 °C, 40 %RH; Jungle 35 °C, 50 %RH<sup>3</sup>; and Desert, both 49 °C, 20 %RH and 40 °C, 30 %RH. Minimal to light ( $\sim 1-3$  m·sec<sup>-1</sup> [ $\sim 2.2-6.7$  mph]) wind speed is recommended, but should be consistent ( $\pm 0.09$  m·sec<sup>-1</sup> [ $\pm 0.2$  mph]) for all comparable tests. Efforts to simulate "solar load" during human chamber studies are not recommended. Most chambers simulate solar radiation with a bank of infrared heat lamps. Unless the chamber and

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<sup>3</sup>While 75 %RH is the standard "jungle" environment for biophysical testing, 50 %RH is a better human test environment. At 50 %RH, the skin-to-ambient vapor pressure gradient allows for some evaporation through clothing, and will not so severely shorten work time as to render the data too limited for garment comparisons.

radiation sources are designed for this purpose, the radiant load is unevenly distributed, and the lamps do not simulate the natural spectral distribution (Dr. W.R. Santee, personal communication; see Breckenridge and Pratt, 1961, for more information on solar load and clothing).

For Field Studies: The ambient weather conditions should be closely monitored at all times (at ~15-min intervals during testing at the test site) so that all evaluation trials can be scheduled during ambient conditions that are as similar as possible. Accurate ambient measurements ( $T_{db}$ ,  $T_{wb}$  or  $T_{dp}$ ,  $T_{bg}$ , possibly  $T_{soil}$ , and wind speed) should be used to describe test conditions for data reporting, and may have to be used in an analysis of co-variance if conditions are not identical among test days.

The heat stress tests should be at least 2 hours in duration and employ moderate intensity exercise (~325 to 500 watts or about 25-50% of the subject's maximal aerobic power). Exercise intensity relative to clothing and environment should be such as to allow for steady-state exercise measurements for at least 60 min. The exercise bouts need to be long enough to ensure steady-state physiological responses, when biophysically possible, and allow for the response time of the employed core temperature index (Sawka and Wenger, 1988). Continuous exercise or 50-min exercise bouts spaced by 10-min rest periods (during which the subjects are weighed and rehydrated) have been used successfully.

**Monitoring Physiological Variables:** The appropriate measurement of core body temperature is central to a garment evaluation relative to heat strain (Sawka and Wenger, 1988). Core body temperature should be monitored during all heat exposures. For the purpose of garment comparisons, core temperature should be measured either at the rectum (~10-12 cm past anal sphincter) or the esophagus (at level of the left atrium, inserted ~25% of subject's height from tip of sensor to entry at nostril). These sites accurately reflect small changes in central arterial blood temperature and are not biased by environmental conditions (Sawka and Wenger, 1988). While esophageal temperature ( $T_{es}$ ) responds more quickly to changes in central blood temperature, it is not as compatible with use of CP masks. Also,  $T_{es}$  reflects changes in temperature caused by swallowing and drinking. For these reasons,  $T_{re}$  is most widely used for garment comparisons. Rectal temperature ( $T_{re}$ ) is

measured from a flexible thermistor (Yellow Springs Instruments, Yellow Springs, Ohio). Core temperature measured at the auditory canal/tympanic membrane is not acceptable (Sawka and Wenger, 1988), and ingestible "pill" temperatures do not always track well with rectal and esophageal values (Kolka et al., 1993; Quigley et al., 1992; Sparling et al., 1993; Stephenson et al., 1992). (For a summary of the main advantages and disadvantages of the various measurements of core temperature, see Table 2.)  $T_{re}$  should be continuously monitored, and should be recorded at least every 5 min (every 1 min if possible). In the field  $T_{re}$  can be monitored with a portable system that displays temperature (Beckman Industries digital thermometer); temperatures must then be recorded manually. A portable data acquisition system that displays and stores data ( $T_{re}$ ,  $T_{sk}$ , heart rate) is preferable (Grant squirrel digital meter/logger).

Heart rate (HR) should be monitored during exercise and during all heat exposures. Heart rate is measured via a bipolar electrode placement and may also be monitored by use of an electrode band worn around the chest while HR is recorded on a wrist monitor. In the field, HR can easily be monitored using the portable wrist monitor (one type used successfully is the Polar Vantage XL #45900) or by use of a portable data acquisition system. Heart rates should be continuously monitored, and should be recorded at least every 5-10 min. ( $T_{re}$  and HR criteria for stopping a test are described in the section "Minimizing Risks.")

During the garment tests, skin temperature should be measured at a minimum of three sites. Because skin temperatures are not generally uniform across the body, they are usually expressed by a mean-weighted skin temperature ( $\bar{T}_{sk}$ ). Mean skin temperatures that are based on regional weighting according to the percentage of body surface area are particularly useful for the calculation of mean body temperature and heat storage. One accepted mean-weighting for skin temperatures is the equation developed by Ramanathan (1964), where:  $\bar{T}_{sk}, ^\circ\text{C} = 0.3$  (chest+upper arm temperatures) +  $0.2$  (thigh + calf temperatures). Skin temperatures are commonly measured from temperature sensors in contact with the skin's surface. A four site (calf, thigh, forearm, chest) or three site (calf, forearm, chest) skin temperature is usually used, and  $\bar{T}_{sk}$  is calculated (Ramanathan, 1964; Burton, 1935). (For discussion on  $\bar{T}_{sk}$ , see Sawka and Wenger, 1988.)  $\bar{T}_{sk}$  should be monitored continuously, and

should be recorded at least every 5 min (every 1 min if possible). If  $T_{sk}$  are to be measured in the field, a portable data acquisition system (described above for  $T_{re}$ ) may be used.

Because the water-vapor permeability of clothing has a major effect on the wearer's rate of evaporation, garment comparisons should include measurement of total and evaporative sweating rates. Sweating rates at a specific site (e.g., chest, arm, back) can most accurately be measured from a dew point temperature sensor (Graichen et al., 1982). For the purpose of garment comparisons, determining whole-body sweating rate and the percentage of the total that evaporates, pre- to post-tests weights are critical. Pre- and post-test nude (or minimally clothed; i.e., shorts, T-shirt, no shoes) weights should be measured each day of heat acclimation and testing. Pre- and post-test dressed weights, and the weights of the clothing alone, should be measured for each of the garment tests. Post-test weights (body and clothing) should be measured as soon as possible following heat exposure, for two reasons: 1) Sweat evaporation from clothing will skew estimations of the evaporated sweat. 2) The test subjects should begin rehydrating as soon as possible after testing. Total body sweating rates (and the evaporative component) can be determined from nude body weight changes from pre- to post-exercise, corrected for fluid ingestion, urine output, and water trapped in the garment. Sweating rate measured in this way should be expressed per unit time and per unit surface area ( $\text{g}\cdot\text{m}^{-2}\cdot\text{h}^{-1}$  or  $\text{L}\cdot\text{h}^{-1}$ ). In the field, sweating rates may be estimated in the same way, though it is often not possible to get post-test nude and clothing weights immediately after testing.

Metabolic rate is often determined (via open circuit spirometry) during familiarization sessions conducted prior to the actual garment tests. If CP masks and/or totally encapsulating garments are tested, metabolic rate need not be determined during the trial. If measurement of metabolic rate will not interfere with the garments being tested, then it should be determined during actual testing. In the field, metabolic rate can be determined during familiarization or testing by use of a portable instrument (the "oxygen consumption monitor," Oxylog, P.K. Morgan Instruments, Inc., Andover, MA, has been used successfully).

Subjective measurements (usually from rating scales or questionnaires) are often collected during garment evaluations. This information can be useful to garment developers, users and to CHPPM(P). Periodically during the garment tests (once or twice during each cycle of rest and exercise) the subjects may be asked to rate their perception of effort based on the Borg Scale (1970, 1982), and their thermal sensations based on a scale modified from Gagge (Gagge et al., 1967; Young et al., 1987). A questionnaire can be used to assess subjective heat strain. Twenty-two questions selected from the Environmental Symptoms Questionnaire are described by Johnson and Merullo (1993). All of these subjective measures can provide information on the volunteer's perceptions, but are of limited value relative to physiological measurements.

Table 2

CORE TEMPERATURE MEASUREMENTS  
ADVANTAGES and DISADVANTAGES

SITE	ADVANTAGE	DISADVANTAGE
ESOPHAGEAL	ACCURATE RAPID RESPONSE	AFFECTED BY SWALLOWING CAN BE UNCOMFORTABLE
ORAL	EASY TO USE	AFFECTED BY DRINKING AFFECTED BY MOUTH BREATHING
PILL	EASY TO USE	AFFECTED BY LOCATION IN G-I (LOCATION is VARIABLE and UNCERTAIN) AFFECTED BY DRINKING
RECTAL	ACCURATE	SLOW RESPONSE CAN BE UNCOMFORTABLE
TYMPANIC	EASY TO USE RAPID RESPONSE	INACCURATE AFFECTED BY AMBIENT and SKIN TEMPERATURES CAN BE UNCOMFORTABLE

## **Laboratory vs. Field Studies**

Laboratory studies conducted in environmental chamber facilities allow for measurement of thermal strain when garments are worn in carefully controlled conditions. Field testing can provide data under actual operational scenarios (where test parameters can be measured although not closely controlled). Controlled environmental and exercise conditions in the laboratory allow for more sophisticated and controlled data collection. Questions such as these are best answered by laboratory studies: "What, if any, differences are there in heat stress between tested clothing ensembles?", "Which ensemble imposes the least heat strain?", and "How much longer or shorter are work times in garment A vs. B?". Close medical monitoring decreases risk to volunteers. The limitations to human testing are that it costs the most in time and dollars, hence fewer conditions can be tested, and users may not trust results from nonrealistic scenarios. Table 3 summarizes the pros and cons of laboratory (environmental chamber) vs. field testing.

CHPPM(P) may determine (or Project Managers may request) that a HS field study is needed. When critical questions regarding garment comparisons need to be made, field testing should be conducted in addition to, not in lieu of, laboratory testing. Advantages of field studies are that they may be mission relevant with respect to location and activity, and often to the workers who volunteer as test subjects. Limitations of field studies are the lack of controls (environment, work), lack of sophisticated measurement and data acquisition methods and, consequently (limited at best or meaningless at worst), usefulness of the data.

While we can measure many of the same physiological parameters in both chamber and field tests, data from chamber tests are more readily analyzed and more meaningful if the purpose of the test is to quantify heat strain and to make comparisons among garment systems. The reasons for this are 1) the environmental conditions in the laboratory can be controlled so that all trials are comparable; the environment doesn't change during a test or from one test to another; 2) the work load (exercise intensity, duration, activity) can be controlled so that all trials are quantifiable and comparable; and 3) the physiological measurements are more reliable. During carefully controlled laboratory testing, data collected is not confounded (few or no

unrelated/unplanned effects) and can be analyzed so that even subtle differences may be revealed. Statistically and physiologically significant differences may not always coincide. Nonconfounded data help in assessing not only where significant differences may be, but also which are meaningful from a practical point-of-view.

Table 3

# HEAT STRESS TESTING CHAMBER vs FIELD TESTING, PROs and CONs

	Chamber Testing	Field Testing
Climate Control	<ul style="list-style-type: none"> <li>• Consistency (<math>\pm</math>) during and among tests as follows: <ul style="list-style-type: none"> <li>• Temperatures (db,bg,wb,dp), <math>\pm 0.5^{\circ}\text{C}</math></li> <li>• Humidity <math>\pm 1\%</math></li> <li>• Wind Speed <math>\pm 0.1 \text{ m}\cdot\text{s}^{-1}</math> (0.2 MPH)</li> <li>• No solar load</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Except to choose a location, season, day and time of day in which to test, there is no control.</li> <li>• Even the most predictable climates can be inconsistent during and among tests.</li> </ul>
Control of Metabolic Heat Production	<ul style="list-style-type: none"> <li>• Exercise can either be set to an absolute (the same for everyone), or relative (percent of individual maximal) intensity. In either case, the exercise intensity, and thus metabolic heat production, can be exactly reproduced.</li> </ul>	<ul style="list-style-type: none"> <li>• Even on the most carefully measured and timed courses, it is difficult to reproduce exercise intensities.</li> <li>• Realistic operational scenarios provide the least opportunity for reproducibility.</li> </ul>
Operationally Relevant	<ul style="list-style-type: none"> <li>• Exercise intensity, and therefore heat production, only approximates that of operational activities.</li> <li>• Specific operational tasks will not usually be used in the laboratory because they cannot be accurately reproduced.</li> </ul>	<ul style="list-style-type: none"> <li>• Authentic activities vary within and among individuals.</li> <li>• Realistic scenarios may provide a sense of what a materiel will be like during use.</li> <li>• These activities are important for operational and human factors tests, but are of limited value for physiological heat strain evaluations.</li> </ul>
Physiological Measurements	<ul style="list-style-type: none"> <li>• Proven Technologies: <ul style="list-style-type: none"> <li>• Core Temperature (rectal or esophageal)</li> <li>• 3-10 Point Skin Temperature</li> <li>• Metabolic Rate</li> <li>• Heart Rate</li> <li>• Sweating Rate</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Experimental and/or variable and/or fragile technologies: <ul style="list-style-type: none"> <li>• Core Temperature (rectal or telemetry pill)</li> <li>• some skin temperatures possible</li> <li>• Metabolic Rate</li> <li>• Heart Rate</li> <li>• Sweating Rate</li> </ul> </li> </ul>
Data Analyses	<ul style="list-style-type: none"> <li>• Controlled test conditions allow for "clean" data collection and analyses, which in turn allow for confident evaluation of human responses to heat stress relative to materiel systems.</li> </ul>	<ul style="list-style-type: none"> <li>• Confounded data make analyses more complicated (i.e. ANCOVA) and results more difficult to interpret.</li> </ul>

Figure 3. Soil temperature in the desert during 4 test days (~0800-1200 h). (from Levine et al., 1993)

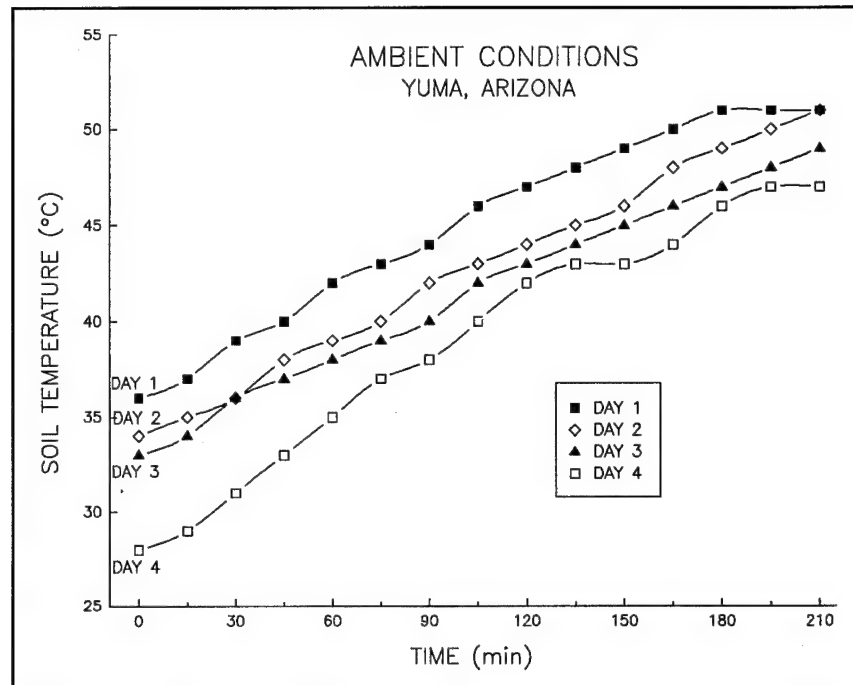


Figure 3 illustrates the soil temperature ( $T_{\text{soil}}$ ) for each of four test days, during the time of testing (Levine et al., 1993). There were significant differences in  $T_{\text{soil}}$  between test days; day 1 was hottest, and each day was progressively cooler than the previous day. (Not only was day 1 hottest, day 3 was driest, windiest, and least sunny; while day 2 was hotter than day 4, it was also drier and windier.)  $T_{\text{soil}}$  was used in these analyses to determine if there were differences between ambient conditions from one day to the next, because  $T_{\text{soil}}$  is most closely associated with the black globe temperature ( $T_{\text{bg}}$ ), and the effective radiant flux, which both take into consideration the ambient temperature and the solar heat load. Also, the  $T_{\text{bg}}$  is linearly correlated with the measurement of core body temperature, whereas other measures commonly used to characterize ambient conditions (WBGT, ambient temperature as  $T_{\text{db}}$ ) are not. (Adolph, 1947; Breckenridge and Goldman, 1971; and personal communication with Dr. Richard R. Gonzalez and Mr. John R. Breckenridge). Since for these data there were more accurate and frequently obtained data for  $T_{\text{soil}}$  than for  $T_{\text{bg}}$ , this enabled use of  $T_{\text{soil}}$  in an analyses of covariance (ANCOVA) with repeated measures over time, for the duration of testing. In other words, data was adjusted for the variance of the ambient conditions.

## **Statistical Analyses for Laboratory and Field Tests**

Determination of sample size should be done to estimate the minimum number of test subjects needed to test the null hypothesis of no difference between garment systems (Borenstein and Cohen, 1988). Statistical analysis of the measured variables should include an analysis of variance (ANOVA) with repeated measures, since these studies are of a factorial design. ANOVA is the appropriate statistical analysis for evaluating data from a repeated measures test design (subject x garment x time). When significant main effects are found, a suitable multiple comparison test (e.g., Tukey's Honestly Significant Difference) should be used to determine any significant differences ( $p < 0.05$ ) between levels of the overall significant main effect. Regression analyses can be used to compare the time course changes (slopes) in  $T_{re}$ ,  $T_{sk}$  or HR between the test and control garments. Significance is accepted at the 95% confidence level. Less frequently, t-tests are used (e.g., when there is a comparison of final temperature or endurance time). Test subjects should each serve as their own control. The order of the garment tests should be counterbalanced. Interpretation of the data should be done by the testing agency, or by CHPPM(P) in cooperation with the testing agency. (Data should be in SI units; see Gonzalez, 1985, for conversions.) Interpretation conducted in this manner will optimize clarity and minimize misinterpretation of the test results.

## **Minimizing Risks to the Subjects**

Testing must be conducted in accordance with USAMRMC Regulation 70-25: Use of Human Subjects in Research, Development, Testing and Evaluation (or, for non-DA studies, in accordance with the appropriate regulation for protection of human subjects in research). The procedures recommended in this technical note fall within the framework, restrictions and safety limitations of the USARIEM Type Protocol for Human Research Studies in the areas of Thermal, Hypoxic and Operational Stress, Exercise, Nutrition and Military Performance.<sup>4</sup> Volunteers must be medically screened (history and physical exam) before participation as subjects in any heat stress study, to exclude those with previous heat injury and others for whom the

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<sup>4</sup> See footnote 1 (p. 14), which describes the USARIEM Type Protocol.

combined stress of exercise and hyperthermia may pose a greater hazard than for normally healthy persons. Persons should not be included in HS garment studies if they have any history of heat injury or illness, chronic respiratory illness, or skin disorders that would affect sweating and/or heat transfer, thus putting them at increased risk. Usually persons with orthopedic problems (legs, feet and back especially, that might be exacerbated by treadmill walking) will not be selected. Female volunteers who are not pregnant (serum pregnancy test required) will be considered as test subjects if they meet other criteria. (The USARIEM Type Protocol, 1994, outlines recommended medical criteria. Note additional criteria for subjects over 35/40 yrs. Volunteers who are over 40 (over 35 if risk factors are also present) must have a graded (12-lead EKG) exercise test in the presence of a cardiologist.)

For all studies, a medical officer/medical monitor<sup>5</sup> must be on site or readily available. For field studies, a trained medic and ambulance service should be on site or readily available. Air-conditioned areas should be available on site or nearby, and a clinic or hospital should be within a few-minutes ambulance drive away. Some degree of dehydration and hyperthermia is expected. Drinking water must be available at all times during testing (even if a particular test or portion of a test requires no drinking), and subjects should be encouraged to drink.

When subjects participate in the HS tests described in this TN, there is a risk of injury, which may be heightened when visibility is impaired due to the protective masks, when subjects are dehydrated, exhausted, and/or hyperthermic. The risks of injury associated with exercise and hyperthermia are discussed in the USARIEM Type Protocol mentioned above, and should be discussed in the test protocol and in the subject's consent form. To reduce these risks, subjects should be closely monitored at all times (in addition to physiological monitoring). Testing will be discontinued for a subject if he or she exhibits symptoms or signs of impending heat injury, illness or exercise exhaustion. All limits of thermal exposure outlined in the Type Protocol should be adhered to: subjects should be removed from testing, to a cool environment if their  $T_{re}$  rises at a rate exceeding 0.6 °C in 5 min or reaches 39.5 °C (103.1 °F) during exercise or 39.2 °C (102.5 °F) during rest; if heart rate exceeds 90% of measured or age-estimated maximal (220 minus age) for 5 consecutive min during exercise (80% during rest), or 95% of measured or age-estimated maximal at any

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<sup>5</sup> The Medical Monitor is a physician designated in accordance with USAMRMC Regulation 70-25, paragraph 4q.

time; if dehydration reaches 5% of body weight; or if they feel faint, sick or otherwise unable to continue. Testing should also be discontinued for a subject wearing a garment system if there is a failure in the breathing system, the cooling system or in any other aspect of the garment system that may affect test time or the subject's heat storage, if it can't be repaired within 5-10 min. Testing should also be discontinued if the subject requests withdrawal, or at the discretion of the investigator or the medical monitor, whichever comes first. Subjects may voluntarily discontinue testing at any time and withdraw from participation without penalty or prejudice.

In addition to the precautions above, all electrical equipment to be used in direct contact with or in close proximity to the volunteers should undergo an electrical safety check prior to each human use study. All equipment (electrical and otherwise) should be in good working order.

## SUMMARY

The purpose of this TN is to serve as a guide for the evaluation of heat strain imposed by garment systems. The clothing evaluation is primarily in support of the U.S. Army CHPPM(P)'s HHA. The primary objective of the HHA program, in support of the Army materiel acquisition decision process, is to identify and eliminate or control health hazards associated with the life cycle management of, among other things, clothing (DoA AR 40-10). Clothing systems, especially impermeable CP clothing, can exacerbate heat stress caused by a hot environment and/or the work performed by the wearer. The control of the health hazard, heat strain, is of great concern to the Army. If heat strain is allowed to progress it can cause casualties due to heat injury and illness (from heat cramps to heat exhaustion to heat stroke).

There is a progressive relationship among the tests used for a heat strain evaluation. Results from each series of tests (guarded hot plate, manikin, model, and human laboratory and field tests) build on the previous tests, as each provides new information. The heat strain evaluation begins with biophysical evaluations of textile samples and manikin evaluations of the clothing system. The biophysical evaluation also includes prediction modeling based on the results of the manikin tests. Following the biophysical evaluation, a physiological evaluation is conducted with volunteer test subjects. The human tests are generally first conducted in a controlled environmental chamber, and then in the field, if necessary. Considerations in conducting a human heat strain evaluation relative to a clothing system include subjects as their own controls, prototype vs. standard as the control garment, counterbalanced trials, use of healthy subjects and control for circadian periodicity, heat acclimation, hydration, menstrual cycle phase, and eliminating or minimizing mission relevant (but not relevant to garment comparison) accessories and activities.

Decisions that can be made based on GHP test results of several or many candidate textiles include down-selection; some textiles may be eliminated, and some retained based on rank ordering of heat transfer characteristics. From TM tests, some ensembles may be eliminated, some may go on to modeling and human testing, and some may go on to modeling only, based on differences in heat transfer characteristics. From human laboratory tests, ensembles may go on to field testing, especially if CHPPM(P) and/or users have questions about performance during military relevant scenarios. Results of manikin, modeling and human tests provide the

information (thermal characteristics and heat strain) necessary to compare the prototype garment to the standard. The results are used in determining water requirements and feasible and safe work/rest cycles or maximum work times.

CHPPM(P), with the test results from the heat strain evaluations, writes the HHA Report, which may make recommendations for doctrine regarding the safe use of the clothing system.

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## APPENDIX

### GLOSSARY

For an extensive glossary of terms related to thermal physiology, the reader is referred to the reference: IUPS Thermal Commission, 1987. Also see ANSI/ASHRAE 55-1992 (ASHRAE<sub>TM</sub> STANDARD), 1992, for definitions. Many of the definitions in this appendix are taken from those references.

**ACCLIMATION.** physiological change which reduces the strain caused by experimentally-induced environmental stress.\*

**ACCLIMATIZATION.** consists of adaptive changes occurring within the lifetime of an organism in response to stress from the natural climate; these adaptive changes reduce the strain caused by the environment.\*

**HEAT STRESS:** imposed by environment and/or mission to include clothing, work intensity and duration, which may lead to development of physiological strain in exposed individuals.

**Heat Strain:** physiological response to, or consequence of, heat stress; may include heat injury and heat illness, which include the following:

**Heat Cramps:** Painful spasms of the skeletal muscles related to prolonged heat stress.\* Illness due, in part, to excessive loss of salt during sweating. Results in painful muscle spasms in the extremities, back, and abdomen.†

**Heat Exhaustion:** Muscular weakness, fatigue, and distress, with reduced sweating, resulting from prolonged exposure to heat. This condition is aggravated by muscular exertion and by water or salt deficiency.\* Illness due to circulatory failure in which venous blood returned to the heart is significantly reduced, and can lead to fainting. Failure is caused because the individual's blood supply is not adequate to serve both heat regulation and other bodily needs.†

**Heat Stroke:** An acute syndrome caused by an excessive rise in core body temperature as the result of overloading or failure of the thermoregulatory system during exposure to heat stress. It is characterized by a large variety of pathophysiological alterations of bodily functions, including mental disturbances, with a high incidence of permanent damage or fatality.\* Illness is due to the core body temperature reaching a level where sweating stops. The body temperature can then rise to critical levels causing tissue damage and death.†

**HEAT LOSS - SENSIBLE HEAT LOSS/DRY HEAT LOSS:** The sum of heat that flows or fluxes by radiation, convection, and conduction from a body to the environment.

**HEAT LOSS - INSENSIBLE HEAT LOSS/EVAPORATIVE HEAT LOSS:** Use the term "evaporative heat loss" because of possible confusion with insensible water loss which implies evaporative heat loss but relates to fluid balance. Comprises passive components, i.e., water vaporizing from respiratory surfaces at normal respiration and water diffusing through the skin and vaporizing at the surface (insensible perspiration); its thermoregulatory components are established by autonomic thermo-effectors like thermal sweating...\*

**HEAT TRANSFER TERMS** are determined during manikin testing of garments. The Clo unit is used to express the relative thermal insulation, or the resistance to heat flow of fabrics or clothing (INSULATION)\*.  $1 \text{ Clo} = 6.46 \text{ W/m}^2$  of surface area per degree Celsius difference between  $T_{\text{skin}}$  and  $T_{\text{ambient}}$ .  $i_m$  is a permeability index for evaporative heat loss (PERMEABILITY).  $i_m$  is a dimensionless number from 0 to 1; zero being impermeable.  $i_m/\text{Clo}$  is the ratio of permeability to insulation (EVAPORATIVE RESISTANCE). The higher the ratio  $i_m/\text{Clo}$ , the more potential for evaporation, and therefore heat loss.

**HYPERTHERMIA:** The condition of a temperature regulator when core body temperature is above its set-range and specified for the normal active state of the species. When temperature regulation against overheating is active, hyperthermia is the consequence of the temporary or permanent imbalance between heat load and the capability to dissipate heat. Impairment of temperature regulation may contribute to the development of hyperthermia.\*

**HYDRATION STATUS:** status of total-body water/fluid volume.

**Dehydration:** less than normal/optimal fluid balance, or more specifically, the process of decreasing fluid volume.

**Euhydration:** normally or optimally hydrated.

**Hyperhydration:** more than normal fluid balance, or the process of becoming over-hydrated.

**MACROCLIMATE:** the environment outside the layer(s) of clothing, as the environment outdoors, inside a building, room, tent, or vehicle; macro-climate conditioning refers to traditional ac systems in the living spaces of rooms, vehicles, etc.

**MICROCLIMATE:** the environment between the skin and the clothing, and between layers of clothing; micro-climate conditioning refers to air- or water-cooled vests, undergarments, or to air circulated within a garment, for the purpose of cooling the wearer.

#### **MEASUREMENTS of (HOT) ENVIRONMENTAL CONDITIONS:**

Temperatures for dry bulb ( $T_{db}=T_{\text{ambient}}$  if in air), wet bulb, black globe, and dew point ( $T_{db}$ ,  $T_{wb}$ ,  $T_{bg}$ ,  $T_{dp}$ , respectively), Water Vapor Pressure ( $P_w$ ), wet-bulb globe temperature index (WBGT), Effective Temperature ( $T_{\text{eff}}$ ) (also see "Temperature")

**Radiant Energy:** Energy traveling in the form of electromagnetic waves, to be distinguished from the radiant heat exchange of the environment with the body. That part of the electromagnetic spectrum of significance in thermal physiology is divided into four waveband categories: ultraviolet, visible, infrared, and microwave.\*

**Relative Humidity (% RH):** In thermal physiology, the ratio of the saturated vapor pressure at the dew-point temperature of the enclosure, to the saturated vapor pressure at its dry-bulb temperature.\*

## MEASUREMENTS of HEAT TRANSFER:

**Body Heat Balance Equation:** A mathematical expression that describes the net rate at which a person generates and exchanges heat with its environment (First Law of Thermodynamics). The dimension of the equation and its terms respectively, are in watts (W) but are also expressed in relation to unit area of body surface ( $W \cdot m^{-2}$ ) or to unit body weight ( $W \cdot kg^{-1}$ ).\*

**Radiative:** Rate of heat transfer by radiation, between body and environment, expressed as W or  $W \cdot m^{-2}$ .\*

**Convective:** Rate of heat transfer via movement (down a pressure gradient) of fluids, between body and environment, usually expressed W or  $W \cdot m^{-2}$ .\*

**Conductive:** Rate of heat transfer via movement (down a thermal gradient) of adjacent particles (of air, liquid, or solid matter; of minimal importance in upright humans in air), expressed as  $W \cdot m^{-2}$ .\*

**Evaporative:** The rate at which heat energy is transferred by evaporation from, or condensation on the skin and the surfaces of the respiratory tract, usually expressed in terms of unit area of total body surface.\*

**MEASUREMENTS OF PHYSIOLOGICAL STATUS:** Core Body Temperature via Rectal, Esophageal, Telemetry Pill ( $T_{re}$ ,  $T_{es}$ ,  $T_{pill}$  respectively), Mean Weighted Skin Temperature ( $\bar{T}_{sk}$ ) (3, 4, 8 sites in hot,  $\geq 10$  sites in cool environments), Sweating Rate ( $\dot{m}_{sw}$ ), Oxygen Uptake ( $VO_2$ ), Maximal oxygen uptake or maximal aerobic capacity ( $VO_{2max}$ ), Heart Rate (HR), Heat Storage ( $W \cdot m^{-2}$ )

**The PHEL CHART:** deals with time-weighted-mean limitations on an individual's work capacity in hot environments (afloat) (Appendix C (Attachment A) TB MED 507, and NAV MED P-5010-3 (Manual of Naval Preventive Medicine). Also see United States Air Force (USAF) Fighter Index of Thermal Stress (FITS) developed at the USAF School of Aerospace Medicine by Stribley and Nunneley (SAM TR-78-6, USAFSAM [VNT]).

SOLAR LOAD: Net radiation balance consists of 3 incoming solar components, 2 incoming infrared components (thermal), and 1 outgoing (emitted) infrared component. Natural solar load is nearly always in transition; it depends on latitude, time of day and year, cloud cover, ground cover and position of the subject. (Dr. Santee, personal communication; also see Radiant Energy definition above.)

TEMPERATURE: WBGT Index and WBGT threshold values: for instituting proper preventive measuring during hot weather in Armed Forces industrial-type settings ashore (Appendixes A and B, TB MED 507).

Effective Temperature, Rational Temperature: ( $T_{eff}$ ) An arbitrary index which combines in a single value the effect of temperature, humidity, and air movement on the sensation of warmth or cold felt by human subjects. The numerical value is that of the temperature of "still" air saturated with water vapor which would induce an identical sensation ( $^{\circ}\text{C}$ ) \* (also Corrected Effective Temperature).

\* Definitions from IUPS Thermal Commission, 1987.

† Definitions from HHA Assessor's Guide, CHPPM(P), (in review).

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